

# Direct Distance Measurements to SN 2009ip

M. Potashov<sup>1\*</sup>, S. Blinnikov<sup>1,2,3†</sup>, P. Baklanov<sup>1,2‡</sup>, and A. Dolgov<sup>1,2,4§</sup>

<sup>1</sup>*Novosibirsk State University, Novosibirsk 630090, Russia*

<sup>2</sup>*Institute for Theoretical and Experimental Physics, Moscow 117218, Russia*

<sup>3</sup>*Sternberg Astronomical Institute, Moscow State University, Moscow 119992, Russia*

<sup>4</sup>*University of Ferrara and INFN, Ferrara 44100, Italy*

Accepted 2013... Received 2012...; in original form 2012...

## ABSTRACT

We show applicability of our new method, Dense Shell Method (DSM), for measuring astronomical distances using an example of supernova SN 2009ip, which had several outbursts. The method is based on the original Baade idea. Distance to this supernova is well measured via Cosmic Distance Ladder and generally assumed to be 20.4 Mpc. Our method directly gives a very close result, namely we find that the median distance is  $\approx 20.1 \pm 0.8$  (68% CL) Mpc to SN 2009ip assuming the most reasonable values for its parameters.

**Key words:** supernovae: cosmography – supernovae: individual (SN 2009ip)

## 1 INTRODUCTION

We (Blinnikov et al. 2012) have introduced a new method for measuring cosmological distances, which we suggest to call the Dense Shell Method (DSM). The method relies on the formation of an expanding dense shell in SN IIn and allows to find a linear size of a supernova shell in absolute units and distance to it without help of the cosmological distance ladder. Using this method Blinnikov et al. (2012) have calculated the distance to SN 2006gy. But the result contains quite a large error due to uncertainty of the interstellar extinction and the color temperature. Moreover, there is a small number of observations of the rising part of the light curve when the shell is believed not to fragment. In this paper, we examine applicability of our method for the case of the supernova SN 2009ip, which exploded again in 2012. We show that the accuracy of the DSM distance determination in this case is much higher.

## 2 DIRECT DISTANCE DETERMINATION BY DENSE SHELL METHOD

Supernovae of type IIn are observed at very large redshifts (Cooke 2008; Cooke et al. 2009; Moriya et al. 2012). They do not enter the coasting free expansion phase, therefore neither EPM (Kirshner & Kwan 1974) nor SEAM (Baron et al. 2004) techniques are directly applicable. Luminous Blue

Variables can eject surface layers several times, filling circumstellar space by an expanding cloud of relatively dense matter. The kinetic energy of those ejecta may be substantially lower than that of the genuine supernova (see Heger & Woosley 2002). Narrow lines in the spectra of SN IIn imply that the matter of first ejections has velocity an order of magnitude lower than in the case of the ordinary supernovae (see Grasberg & Nadezhin 1986).

SN 2009ip has produced several outburst which were observed directly. The physical mechanisms of those ejections can be different (Heger & Woosley 2002; Chevalier 2012; Soker & Kashi 2012). The time between the outbursts can greatly vary. If this time is large enough, a “dip” can be formed between the star and the locus of the maximum density of the cloud. If one imagines that the LBV giant surrounded by such a cloud from the primary explosion would outburst again as a genuine supernova or produce a similar but high-velocity outburst the new ejected material will have much higher velocity. So in the first days after the shock breakout, ejecta would fly through the surrounding low-density “dip” of the cold and thus transparent cloud. The spectra would contain only the broad lines born in the high-velocity ejecta. Ejecta would propagate and collide with the high-density cloud layers. Shock waves would run to both sides of the locus of the collision, forward (into the cloud) and backward (into the ejecta).

In what follows we consider only spherically symmetric outbursts. Our calculations show that the velocity of these shocks relative to ejecta is low. This is an inevitable consequence of the mass continuity (see Eq.9 in Blinnikov et al. 2012, and its discussion). One can consider both shocks as “glued together” into dense shell. Moreover, all the ki-

\* marat.potashov@gmail.com

† sergei.blinnikov@itep.ru

‡ baklanovp@gmail.com

§ dolgov@fe.infn.it

netic energy of the matter accreted onto the dense shell is radiated away. That is why we call this structure cold dense shell (hereafter CDS). Nevertheless, the region of the cloud in front of the CDS will be heated up and shine in narrow spectral lines. Depending on the optical depth of the heated cloud, CDS may shine out (Chugai et al. 2004; Woosley et al. 2007). In this case the observed spectrum may have narrow lines on a broad pedestal. In addition, the matter of the cloud will be accumulated in the CDS, gradually breaking it, and eventually the neglect of the relative shock velocities becomes incorrect. In future evolution one has to investigate the stability of CDS (see van Marle et al. 2010).

The calculations show that under certain conditions the photosphere is close to the CDS and moves together with it (e.g., 2006gy, Woosley et al. 2007; Blinnikov et al. 2012). One may find the matter velocity from the broad spectra features which determine the photosphere velocity,  $v_{ph} = dR_{ph}/dt$ .

After that a set of models is built, which well describes the time dependence of the flux, the color temperature, the cloud and ejecta velocities and the cloud density. Such models do not necessarily correspond to the same distance to the star. DSM will “scale” the set of models to the desired distance by changing the radius of the photosphere.

Let the initial radius (unknown to us) is  $R_0$ , and  $R_i \equiv R_0 + \Delta R_i$  for  $i = 1, 2, 3, \dots$ , where  $\Delta R_i$  is already known from  $dR$  integrated over time. We assume here that the observations are sufficiently frequent to allow measurements of the increments in radius  $dR_{ph} = v_{ph}dt$  for a number of points, where  $dt$  is a difference of time of the successive observations.

Then we use Eq. 4 from (Blinnikov et al. 2012):

$$\zeta_{\nu i}(R_0 + \Delta R_i)\sqrt{\pi B_{\nu}(T_{cvi})} = 10^{0.2A_{\nu}} D \sqrt{F_{\nu i}}. \quad (1)$$

Here  $\zeta_{\nu i}$  is the dilution factor,  $T_{cvi}$  is the color temperature, obtained from the spectrum, function  $B$  is the blackbody intensity,  $F_{\nu i}$  is the observed flux, and  $A_{\nu}$  is the extinction in stellar magnitudes. All quantities are defined for the frequency  $\nu$ . And finally,  $D$  is an unknown distance to the star.

A good model gives us a set of the  $\zeta_{\nu i}$ ,  $T_{cvi}$  for all observational points. From the measured  $F_{\nu i}$  and  $\Delta R_i$  we can find  $R_0$  and the combination  $a_{\nu} \equiv 10^{0.4A_{\nu}} D^2$  by the least square method. Instead of  $\nu$  one may use index  $s$  labelling one of the broad-band filters. To find the distance  $D$  we need to know  $A_s$  e.g. from the astronomical observations.

As we have noticed in (Blinnikov et al. 2012), values of  $\zeta$  do not vary too much from model to model and do not strongly depend on the photospheric radius. In the following we assume the correction factor  $\zeta = 1$ , which is close to the values of  $\zeta$  with accuracy about  $\sim 10\%$  found in our radiation hydro models (Woosley et al. 2007; Moriya et al. 2013) for the growing part of the light curve. Of course, an accurate modelling requires building a hydrodynamical model not only for the light curve but also for spectral line profiles with an account of dilution and projection effects as it has been done for the recent Cepheid models (Gautschi 1987; Sabbey et al. 1995; Storm et al. 2011; Rastorguev & Dambis 2011; Rastorguev et al. 2012).

### 3 DISTANCE TO THE SN 2009ip

We have taken observational data from (Prieto et al. 2012; Mauerhan et al. 2012; Pastorello et al. 2012) and Prieto (2012) web page.

Supernova SN 2009ip began to brighten rapidly after September 24 possibly due to interaction of the ejecta with the circumstellar material (see Prieto et al. (2012) and discussion in Mauerhan et al. (2012)). Unfortunately, starting from September 28 the broad lines mostly disappeared possibly due to the increasing opacity of the heated circumstellar matter, and it becomes difficult to determine the velocity of the CDS (hereafter “shell” = CDS).

We have used a short 2-day period after September 24, when one can determine the velocity of the shell. In addition, at this period the luminosity is proportional to the square of time (Prieto et al. 2012), which corresponds to the constant expansion velocity and color temperature of the photosphere.

Photometric data for SN 2009ip in  $R$  band (Bessell 2005) of all three authors agree well (see footnote 28 in Pastorello et al. (2012)). We have taken the first 36 points of the table<sup>1</sup> from Prieto (2012) web page. These points correspond to the days which are most interesting for us.

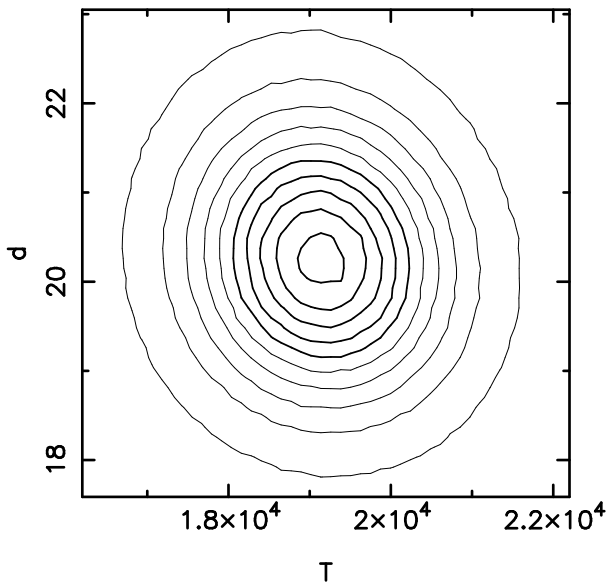
To estimate the expansion velocity  $v$  of the shell we have used the data obtained from the  $H_{\alpha}$  absorption component. At the epoch of a sudden increase of the luminosity of SN 2009ip ( $\sim 23$ -24 September) Pastorello et al. (2012) and Mauerhan et al. (2012) indicate values  $v \approx 13000$  km/s and  $\approx 13800$  km/s, respectively. Of course, a full analysis needs to address the question, which is not yet considered: are the layers of hydrogen excited to the third level (which produced  $H_{\alpha}$ ) close to the photosphere. We have taken the matter velocity equal to  $v \approx 13400$  km/s.

We have adopted an extinction of  $A_R = 0.051$  mag following Mauerhan et al. (2012). In view of the smallness of this value,  $10^{0.2A_R}$  is close to unity. The error in  $A_R$  has very little effect on the final answer. We have taken 0.001 mag for the error value and did not evaluate the impact of its changes on the final result.

Prieto et al. (2012) obtains black-body temperature in two different ways. The first black-body fit takes into account the data from  $R$  and  $I$  filters and has a value  $T \approx 14500$  K. The second fit uses the longer wavelength coverage (from near-UV to  $V$ -band) and the temperature  $T \approx 19200$  K. Prieto et al. (2012) treats the obtained values as effective temperatures, but the method of obtaining them corresponds to color temperatures. In our method these values are used as color temperatures.

To estimate the confidence intervals of the distance we have done a resampling Monte Carlo (MC) simulation based on these data. We resampled the values of  $T$ , of the stellar magnitude  $m_R$  in standard filter  $R$ , the reddening  $A_R$ , and velocity  $v$ , each with normal distribution. For some of those quantities we have taken standard deviations from available data or fixed “manually” for illustration if they are not known. For example, since we do not know the error of  $v$ ,  $T$ , we examine how variations in their errors affect the response.

<sup>1</sup> <http://www.astro.princeton.edu/~jprieto/sn09ip/photR.dat>



**Figure 1.** Monte Carlo resampling simulation of the distance  $D$  to SN 2009ip by DSM with respect to temperature  $T$ . The isocontours of probability distribution function (pdf) are shown with equal step in pdf. The observations from (Prieto et al. 2012; Mauerhan et al. 2012; Pastorello et al. 2012) have been used for 36 different time points from Prieto (2012) web page.

For obtaining the confidence intervals for the mean and median distances it was sufficient to do  $10^5$  MC tests.

Taking the temperature of the first Prieto et al. (2012) estimate as  $T \approx 14500$  K and the relative errors in  $v$  and  $T$  equal to 5% we have obtained both the mean and median distances  $D \approx 16.1$  Mpc with 68% confidence interval  $\pm 0.6$  Mpc.

If we artificially increase by factor 2 the relative errors of  $v$ ,  $T$  we find the distance  $D \approx 15.1$  Mpc with 68% confidence interval  $(-1.1, +1.2)$  Mpc. The answer is more sensitive to the error in the temperature.

Taking the temperature of the second Prieto et al. (2012) estimate as  $T \approx 19200$  K and the relative error in  $v$  and  $T$  equal to 5% we have obtained the distance  $D \approx 20.1$  Mpc with 68% confidence interval  $\pm 0.8$  Mpc. For illustration of this case, we have built a slice of multi-dimensional probability density functions in the plane –  $T$  and  $D$ . The plot in Fig. 1 is built with  $10^7$  samples to obtain a better statistics near the top of the distribution. The largest thick-line contour in Fig. 1 is about one standard deviation.

If we increase by factor 2 the relative errors of  $v$  and  $T$  we find the distance  $D \approx 19.9$  Mpc with 68% confidence interval  $(-1.4, +1.5)$  Mpc. The answer is more sensitive to error in the temperature again. In all the cases the error growth leads to smaller median and mean distances.

Those experiments show that the results are rather robust given the level of accuracy of the data and models.

The distance modulus for the galaxy NGC 725, where the SN 2009ip is situated, is generally accepted as  $\mu = 31.55$  mag (Smith et al. 2010) which corresponds to 20.4 Mpc. More detailed and complete studies (like SEAM) without the black-body approximation but with an assistance of a complete hydrodynamical model of the whole

sequence of SN 2009ip outbursts can accurately determine the temperature. However, already now we can say that in the frameworks of our models the temperature estimate  $T \approx 14500$  K is unsatisfactory (if one believes in generally accepted value of the distance). The goal of the current paper is not to obtain the most reliable distance but to show that it can be easily obtained with reliable data. Moreover, increasing the number of the observations would reduce the error in the final result as the square root of the number of observations.

Since the host galaxy NGC 725 is relatively close, the Hubble parameter based only on the redshift  $z$  can be wrong because of a large peculiar velocity of the galaxy. On the other hand, based on the generally accepted value  $H_0 = 71$  km/s/Mpc the resulting value of the distance to the galaxy NGC 725 can be significantly different from the distance obtained by other methods. For instance, Levesque et al. (2012) uses the distance to NGC 725 which is equal to 24 Mpc.

Our distance value is obtained by the new direct method and does not rely on the Cosmic Distance Ladder! It is needed to investigate the role of variations of the correction factors in different SN 2009ip models to check the robustness of our results. We present here the values for  $D$  only for the illustration of the efficiency of the method.

## 4 CONCLUSIONS

We have obtained the distance to SN 2009ip equal  $D \approx 20.1 \pm 0.8$  (68% CL) Mpc. The relative error is much smaller than in the case of SN 2006gy (Blinnikov et al. 2012). If the observations of a supernova are of good quality, and has a large number of data points, the internal error of our method for such supernova will be very small. It is needed to develop a complete supernova SEAM-like model for the comprehensive work of the method, but with complex hydrodynamics taking into account the entire sequence of previous outbursts. One should evaluate the correction factors (e.g. dilution factor) to eliminate possible systematic errors.

The distance we found was based on the spherical symmetric model of the explosion. The fact that it coincides with the generally accepted value shows that the initial epoch of the growth of the SN 2009ip luminosity is well described by an expanding spherical shell.

Constraining of the cosmological parameters and the understanding of Dark Energy depend strongly on accurate measurements of distances in the Universe. Our results on SN 2009ip supports the conclusion that SNe IIn may be used for cosmology as *primary distance indicators* with the new DSM method.

## ACKNOWLEDGEMENTS

S.B. and M.P. are grateful to Alexander Bondar for discussions and encouragement in September and October 2012, when the luminosity of the SN 2009ip exhibited large variations.

The work is supported partly by the grants of the Government of the Russian Federation (No 11.G34.31.0047), by RFBR 10-02-00249, 10-02-01398, by RF Sci. Schools

5440.2012.2, 3205.2012.2, and by a grant IZ73Z0-128180/1 of the Swiss National Science Foundation (SCOPES).

## References

- Baron E., Nugent P. E., Branch D., Hauschildt P. H., 2004, *ApJ*, 616, L91, arXiv:astro-ph/0410153
- Bessell M. S., 2005, *ARA&A*, 43, 293
- Blinnikov S., Potashov M., Baklanov P., Dolgov A., 2012, *Pis'ma v ZhETF*, 96, 167, arXiv:1207.6914
- Chevalier R. A., 2012, *ApJ*, 752, L2, arXiv:1204.3300
- Chugai N. N., Blinnikov S. I., Cumming R. J., Lundqvist P., Bragaglia A., Filippenko A. V., Leonard D. C., Matheson T., Sollerman J., 2004, *MNRAS*, 352, 1213, arXiv:astro-ph/0405369
- Cooke J., 2008, *ApJ*, 677, 137, arXiv:0711.1550
- Cooke J., Sullivan M., Barton E. J., Bullock J. S., Carlberg R. G., Gal-Yam A., Tollerud E., 2009, *Nature*, 460, 237, arXiv:0907.1928
- Gautschi A., 1987, *Vistas in Astronomy*, 30, 197
- Grasberg E. K., Nadezhin D. K., 1986, *Soviet Astronomy Letters*, 12, 68
- Heger A., Woosley S. E., 2002, *ApJ*, 567, 532, arXiv:astro-ph/0107037
- Kirshner R. P., Kwan J., 1974, *ApJ*, 193, 27
- Levesque E. M., Stringfellow G. S., Ginsburg A. G., Bally J., Keeney B. A., 2012, *ArXiv e-prints*, arXiv:1211.4577
- Mauerhan J. C., Smith N., Filippenko A., Blanchard K., Blanchard P., Casper C. F. E., Cenko S. B., Clubb K. I., Cohen D., Li G., Silverman J. M., 2012, *ArXiv e-prints*, arXiv:1209.6320
- Moriya T. J., Blinnikov S. I., Tominaga N., Yoshida N., Tanaka M., Maeda K., Nomoto K., 2012, in Umemura M., Omukai K., eds, *American Institute of Physics Conference Series Vol. 1480 of American Institute of Physics Conference Series*, Type II<sub>n</sub> superluminous supernovae from collision of supernova ejecta and dense circumstellar medium. pp 391–393
- Moriya T. J., Blinnikov S. I., Tominaga N., Yoshida N., Tanaka M., Maeda K., Nomoto K., 2013, *MNRAS*, 428, 1020, arXiv:1204.6109
- Pastorello A., Cappellaro E., Inserra C., Smartt S. J., Pignata G., Benetti S., Valenti S., 2012, *ArXiv e-prints*, arXiv:1210.3568
- Prieto J. L., , 2012, SN 2009ip: High-cadence photometry from Cairns, Australia (J. Brimacombe), <http://www.astro.princeton.edu/~jprieto/sn09ip/>
- Prieto J. L., Brimacombe J., Drake A. J., Howerton S., 2012, *ArXiv e-prints*, arXiv:1210.3347
- Rastorguev A. S., Dambis A. K., 2011, *Astrophysical Bulletin*, 66, 47, arXiv:1011.3305
- Rastorguev A. S., Dambis A. K., Zabolotskikh M. V., Berdnikov L. N., Gorynya N. A., 2012, *ArXiv e-prints*, arXiv:1212.3173
- Sabbey C. N., Sasselov D. D., Fieldus M. S., Lester J. B., Venn K. A., Butler R. P., 1995, *ApJ*, 446, 250
- Smith N., Miller A., Li W., Filippenko A. V., Silverman J. M., Howard A. W., Nugent P., Marcy G. W., Bloom J. S., Ghez A. M., Lu J., Yelda S., Bernstein R. A., Colucci J. E., 2010, *AJ*, 139, 1451, arXiv:0909.4792
- Soker N., Kashi A., 2012, *ArXiv e-prints*, arXiv:1211.5388

- Storm J., Gieren W., Fouqué P., Barnes T. G., Soszyński I., Pietrzyński G., Nardetto N., Queloz D., 2011, *A&A*, 534, A95, arXiv:1109.2016
- van Marle A. J., Smith N., Owocki S. P., van Veelen B., 2010, *MNRAS*, 407, 2305, arXiv:1004.2791
- Woosley S. E., Blinnikov S., Heger A., 2007, *Nature*, 450, 390, arXiv:0710.3314

This paper has been typeset from a  $\text{\LaTeX}$  file prepared by the author.